The Promise of Passively Cooled 10 μm HgCdTe Arrays for NGST

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Requirements imposed by Passively Cooled Focal Planes

- **Why passively cooled focal planes?**
  - **No mechanical cooler required (lower weight, power & complexity, hence expense)**
  - **Extended missions enabled**
  - **Temperatures between 25 and 30K attainable**
  - **"Faster, Better, Cheaper" space missions**
- **Requirements on 10 μm HgCdTe Arrays**
  - **Goal: < zodiacal background current (shown for assumed 4-m telescope, diffraction limited pixels, QE = 70%, telescope and camera efficiencies 81% and 58% respectively)**
  - **Competitive dark currents possible if g-r limited**

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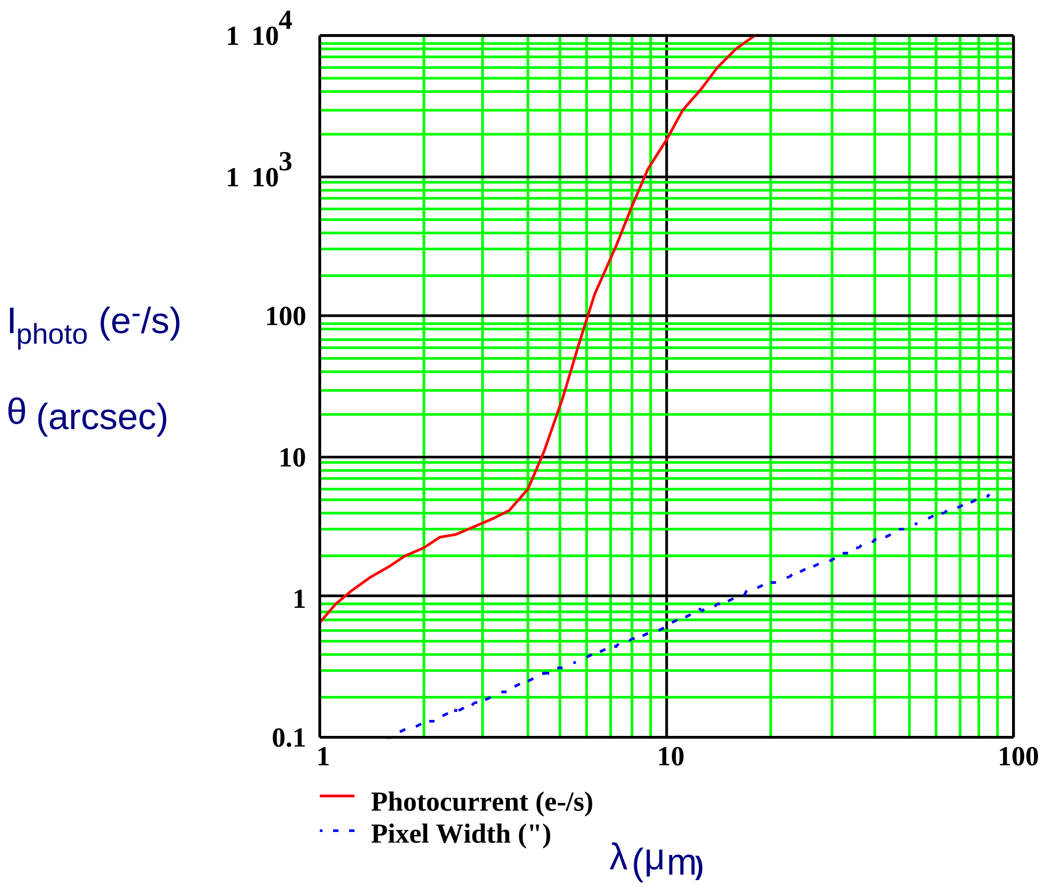
South Ecliptic Pole Zodiacal Background Photocurrent (function of λ)



Requirements on HgCdTe Detectors

- **Fundamental Dark Current Limitations**
  - **For operating temperatures 30K, we model g-r limited dark currents for lifetimes of 10^{-6} s to 10^{-7} s at 10.4 μm of**

    60 to 600 e^-/s for doping density $N_D = 10^{15}$ cm^{-3} and 110 to 1100 e^-/s for $N_D = 10^{14}$ cm^{-3}
  - **g-r limited R_oA's range from $10^{8 \text{ to } 9}$ ohm-cm^2 at 30K to 2 $10^{10 \text{ to } 11}$ ohm-cm^2 at 25K!**
  - **in practice, tunneling limits dark current**
- **Challenge**
  - **Produce 10 μm HgCdTe detectors which exhibit improved dark current at ~30K - *i.e.* reduce N_D and reduce tunneling contributions to dark current**
  - **At the same time, the QE must remain sufficiently high at this low temperature**

Rockwell HgCdTe DLPH Photovotaic Detectors

- **$Hg_{1-x}Cd_xTe$**
  - **tunable band gap with composition x**
  - **high QE and instrinsically rad-hard**
  - **small lattice mismatch between HgCdTe and CdZnTe allows relatively high quality epitaxial heterostructures**
- **Double Layer Planar Heterostructure (DLPH)**
  - **in DLPH, the LWIR material is buried beneath a MWIR material and is never exposed to processing chemicals**
  - **immediately deposited MWIR effectively passivates the surface of the LWIR layer, eliminating the leakage where p/n junction intersects the LWIR/MWIR interface**
  - **Originally, Rockwell used an LPE process: they have now developed a superior MBE DLPH process which is sufficiently mature that there is good material control, low defect density, and good surface characteristics**

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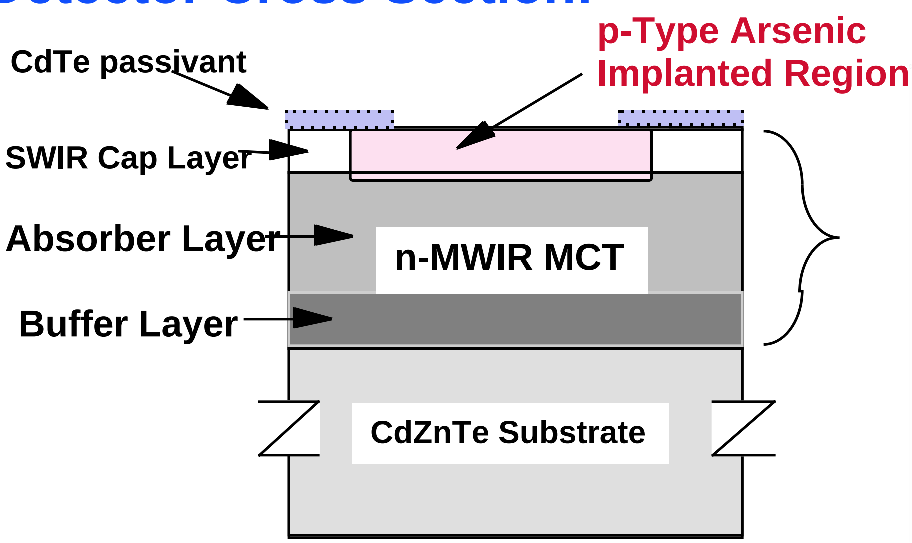
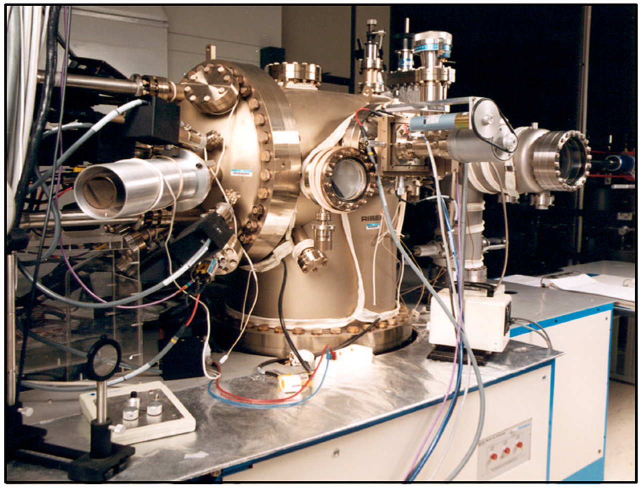
P/N Double Layer Planar Heterostructure--
Offers Performance and Manufacturing Advantages

Detector Cross Section:



RIBER MBE 32-P Growth Reactor



- Inherently High Radiation Hardness
- Inherently Easy to Passivate
- Few Critical Steps Give Reliable Processes
- Excellent Device Performance
- Exploits MBE’s Outstanding Materials Control

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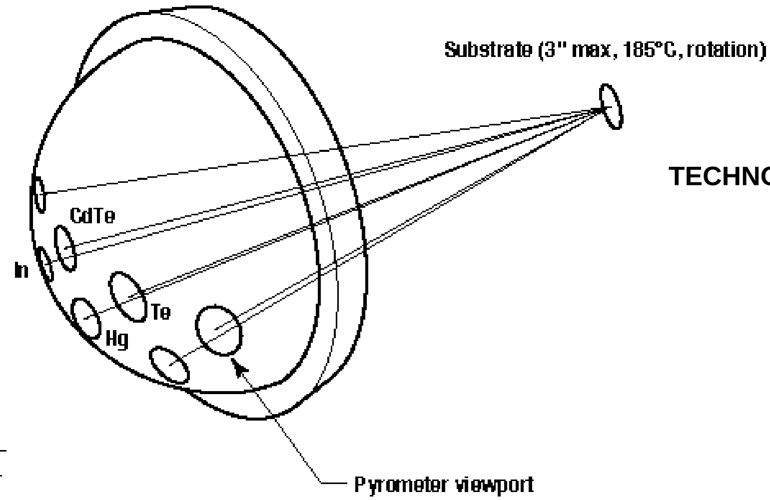
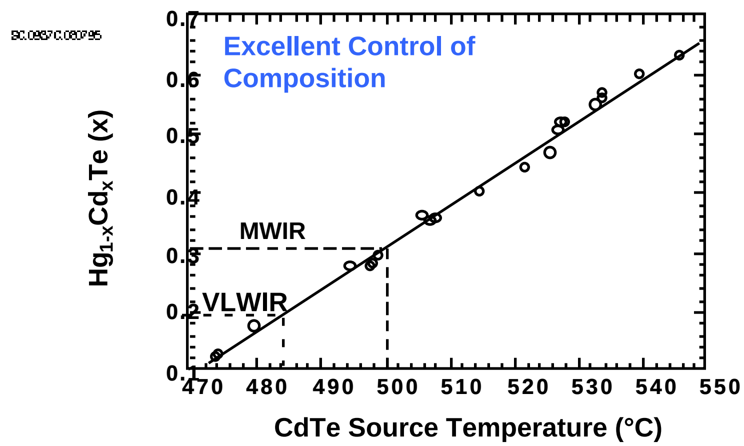
Molecular Beam Epitaxy HgCdTe Growth Technology-

How it is Done



Typical Fluxes

Hg	4.1×10^{-5} torr
CdTe	3×10^{-7} torr
Te	1.5×10^{-6} torr



mean λ_{co}=10.9 µm
std. dev.= 0.18 µm

TECHNOLOGY ATTRIBUTES:

Process Control Refined Due to *In-Situ* Monitoring
Single System Services all IR Applications
Large Area Uniformity
Compositional Control Allows Advanced Structures

LWIR Material Composition Uniformity

x=0.225 λ_{co}=10.8	x=0.223 λ_{co}=11.1	x=0.223 λ_{co}=11.1	x=0.226 λ_{co}= 10.7
x=0.223 λ_{co}=11.1	x=0.226 λ_{co}=10.7	x=0.226 λ_{co}=10.7	x=0.223 λ_{co}=11.1
x=0.223 λ_{co}=11.1	x=0.226 λ_{co}=10.7	x=0.226 λ_{co}=10.7	x=0.223 λ_{co}=11.1
x=0.225 λ_{co}=10.8	x=0.223 λ_{co}=11.1	x=0.223 λ_{co}=11.1	x=0.226 λ_{co}=10.7

4 cm

4 cm

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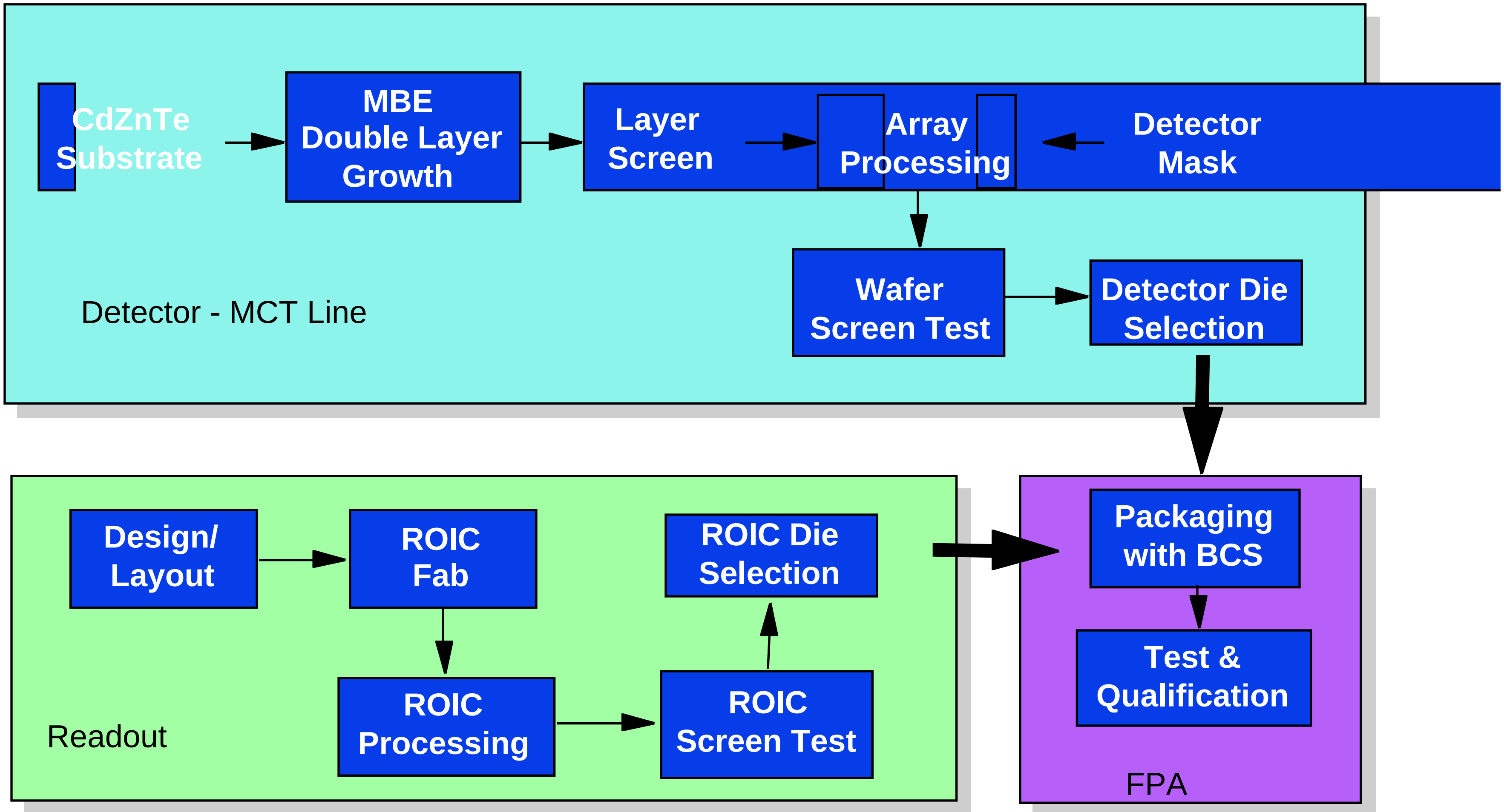
FPA DETECTOR DESIGN AND FABRICATION PERFORMED IN ROCKWELL HgCdTe LINE

FABRICATION ROADMAP



Test Diode Philosophy

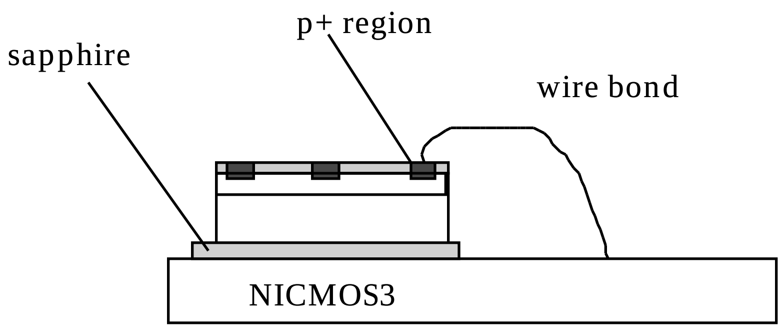
- **Extrapolate from other Rockwell Programs**
  - **Rockwell developing DLPH arrays for low background applications with good 40K performance at λ > 10 μm**
  - **extrapolate from those programs for our lower background applications**
- **Use of NICMOS3 Multiplexer**
  - **Rochester test system set up for low-noise array measurements**
  - **Bonded diodes (e.g. delivery #4, 18-diode wafer) to NICMOS mux with 1 mil wire bonds to Indium bumps on mux unit cell inputs**
  - **Typically one diode connected to 3 - 5 mux pixels**

Detectors Received from Rockwell

- **Delivery 2: 13.7 μm LPE, 5 measurable diodes, $N_D = 1 \times 10^{15}$ cm^{-3}**
  - **test results are consistent with Rockwell's results**
  - **dark current at 50 mV back-bias ~$10^7 e^-$/sec, best $R_0A \sim 2 \times 10^7\ \Omega$-cm^2**
- **Delivery 3: 10.3 μm MBE, 8 measurable diodes, $N_D = 1.7 \times 10^{15}$ cm^{-3}**
  - **because of the high doping density, the dark current performance is not as good as Delivery 2. Also shows large diode to diode variance.**
    - » **dark current has large bias dependence, small temperature dependence - a signature of tunneling**
- **Delivery 4: 10.6 μm MBE, 17 measurable diodes;**

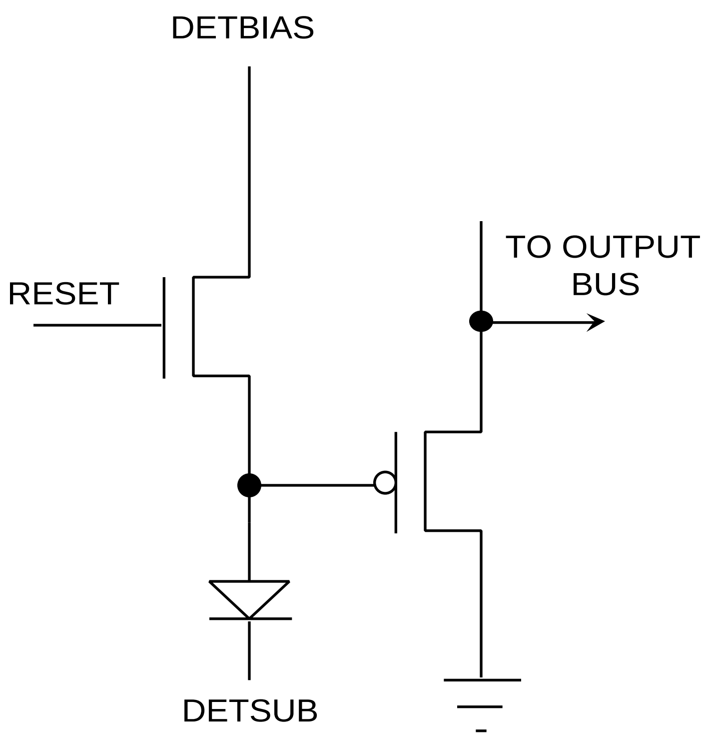
  N_D= 9.5 x 10^{14} cm^{-3}. ***This delivery will be discussed here.***
- **Delivery 5: 10 μm MBE, $N_D = 6.4 \times 10^{14}$ cm^{-3}; 256 x 256 array. Indium-bump-bonded to TCM2620 multiplexer - tests in progress**

Test Structure for Deliveries 1-4



- Diodes are wire-bonded to NICMOS3 muxes
  - **advantages**
    - » **low noise since long integration times and multiple sampling: good for small signals**
    - » **fast I-V curve test**
  - **disadvantage**
    - » **front illumination**
    - » **integration capacitance hard to estimate (multi-nodes/detector)**

Finding the NICMOS Mux Nodes Which Are Connected to the Diodes



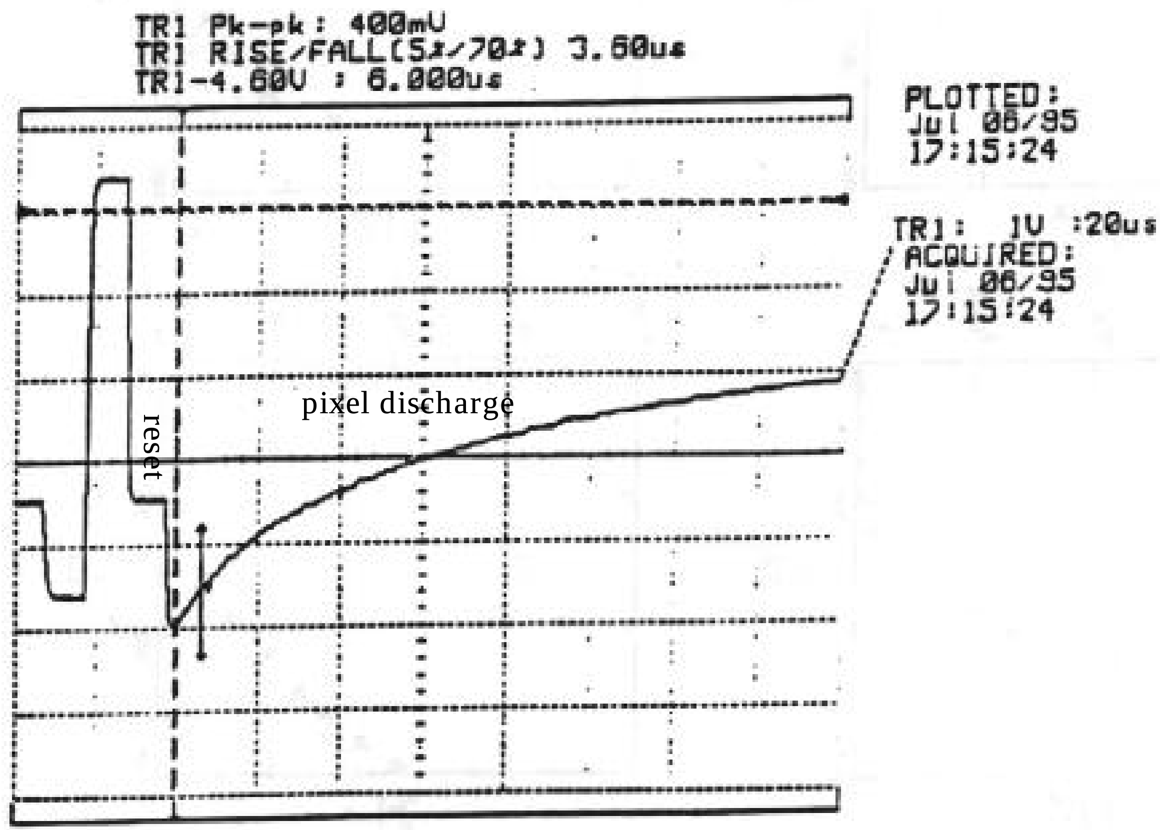
$V_{bias}=V_{DETSUB}-V_{DETBIAS}$

- **Set $V_{DETBIAS}$=-500 mV**
- **Difference of images in uncorrelated single sampling mode with V_{bias}=300 mV and V_{bias}=-200 mV were taken**
- **The pixels with response (> 2500 ADUs) are the pixels bonded to the diodes**
- **Made sure all the responding pixels discharge when the reset switches were turned off.**

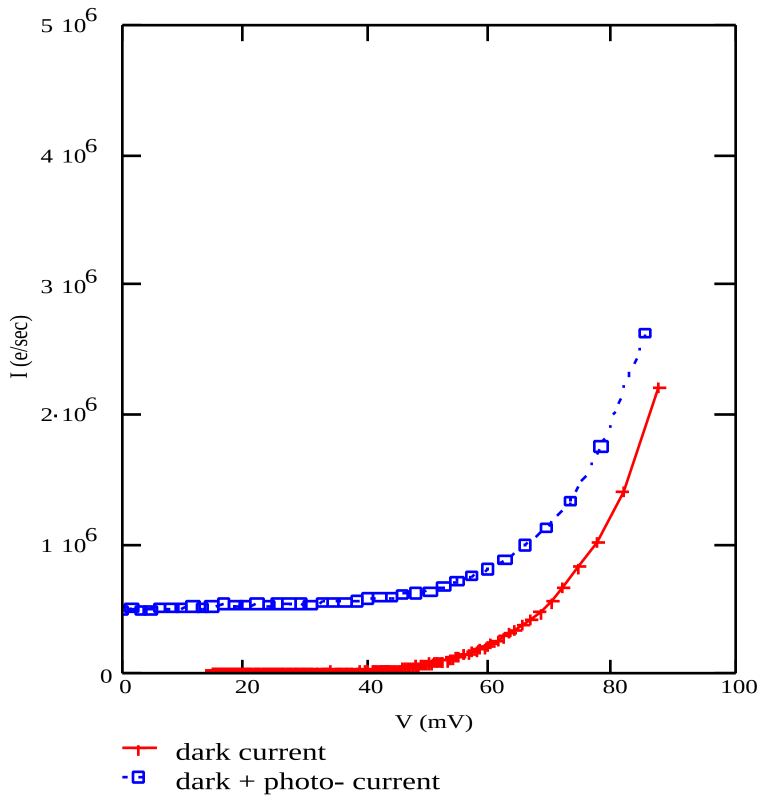
I-V Curve Test

- **Set V_{bias}= 100 mV (actual back bias is about 170 mV, *i.e.* the zero bias point is -70 mV)**
- **Select pixel to be measured and reset it**
- **Turn reset switch off and record the discharging of the output level as a function of time (with 16-bit A/D converter). Oscilloscope trace of discharge next slide.**
- **To deduce the I-V curve**
  - **V=(output level-totally discharged level)/(mux gain x preamp gain)**
  - **I=(C x [*d*(output level)/*dt*])/(mux gain x preamp gain)**
    - » **capacitance C is the integration capacitance, deduced by the Noise^2 *vs.* Signal method**

Detector Discharge

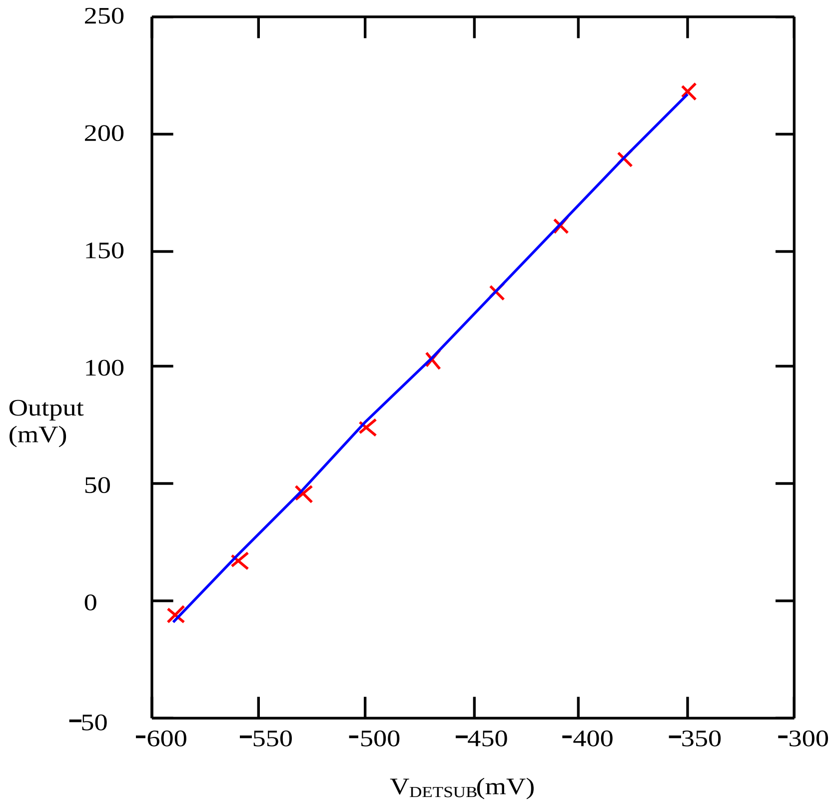


I-V Curves



Typical I-V curve from one of the diodes (#14) from the 4th delivery, T = 30K.

Test Results for Delivery 4: Mux DC Gain

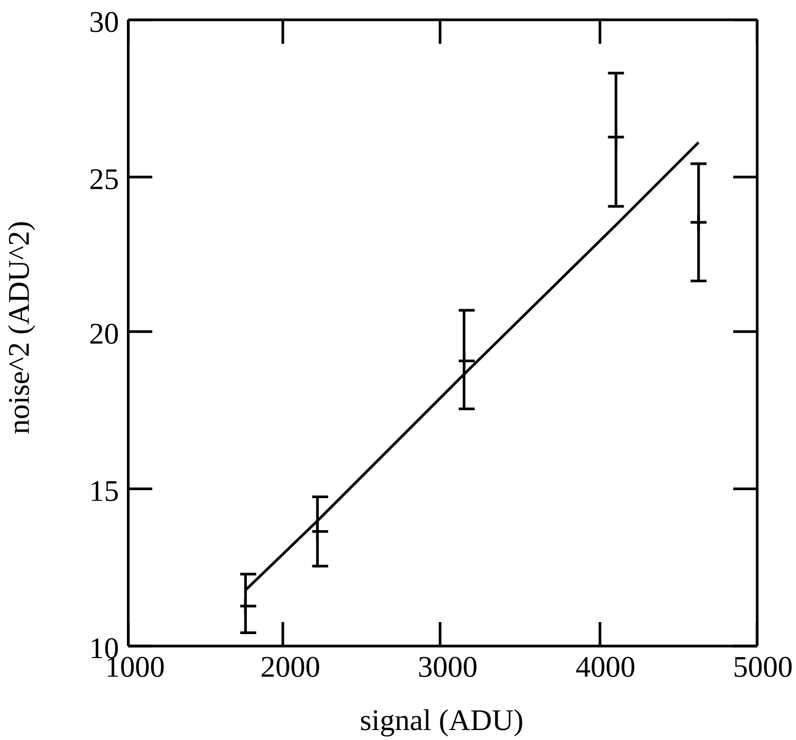


- turn off the reset switch
- discharge the detector
- measure output level *vs.* V_{DETSUB}
- mux DC gain=0.95

Capacitance

- **$C = C_j + N \bullet \langle C_{mux} \rangle + C_{wire} + C_{bump}$**
  - **N - number of mux pixels connected to the diode, *of which 1 is selected***
  - **$\langle C_{mux} \rangle$ - average capacitance of a single mux node (Rockwell estimates 0.04 pF for a *selected* node; capacitance of de-selected nodes larger)**
  - **C_{wire} - estimated to be 0.1 pF**
  - **C_j - junction capacitance calculated from the depletion width, which is a function of the junction area, ε ε_s and N_D: ranges from 0.045 to 0.48 pF for the diodes tested**
- **C measured by the Noise^2 *vs.* Signal method yields higher values for $\langle C_{mux} \rangle$ than 0.04 pF, assuming the other values are either small or well-known**

Test Results for Delivery 4: Capacitance



Squared noise vs. signal for diode #14 from Delivery 4.

- **$C = C_j + N \bullet \langle C_{mux} \rangle + C_{wire} + C_{bump}$**

<u>Delivery #4</u>

- **C for 5 diodes determined by the noise^2 *vs*. signal method, assuming Poisson Noise**
  - » **C = 1.9 pF for diode #14, N = 4**

Test Results for Delivery 4: Dark Current and R_oA

- **At 20 mV reverse bias, 9/14 diodes show dark current < 10^5 e^-/sec (20-40K), 6/14 < 10^4 e^-/s at 30K**
- **9/14 diodes show $R_oA > 10^7$ Ω-cm^2, many as high as 2 - 8 10^8 Ω-cm^2**

Above dark current and R_oA values are computed with C measured by the noise^2 vs. signal method

- **Advanced detector architecture diodes show better performance**
- **Strong bias and weak temperature dependence: implies tunneling dominated dark currents.**

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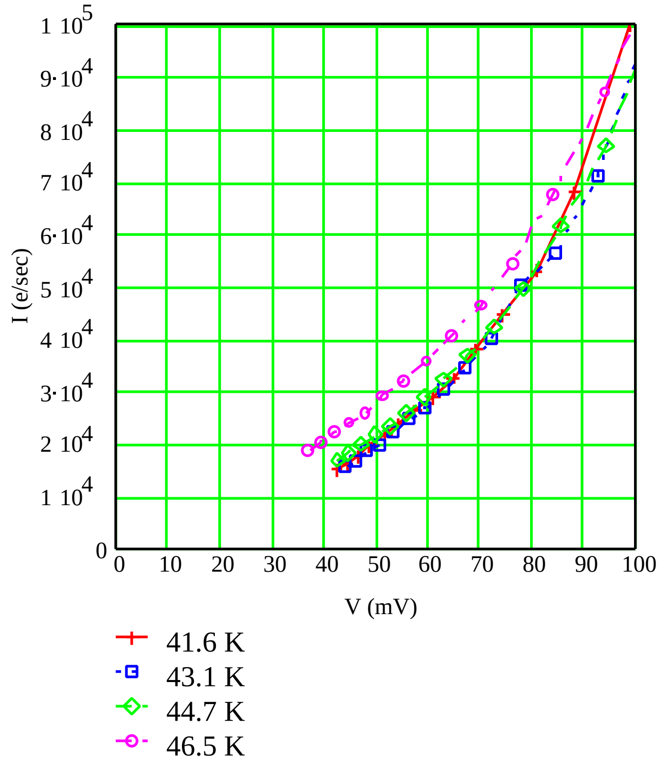
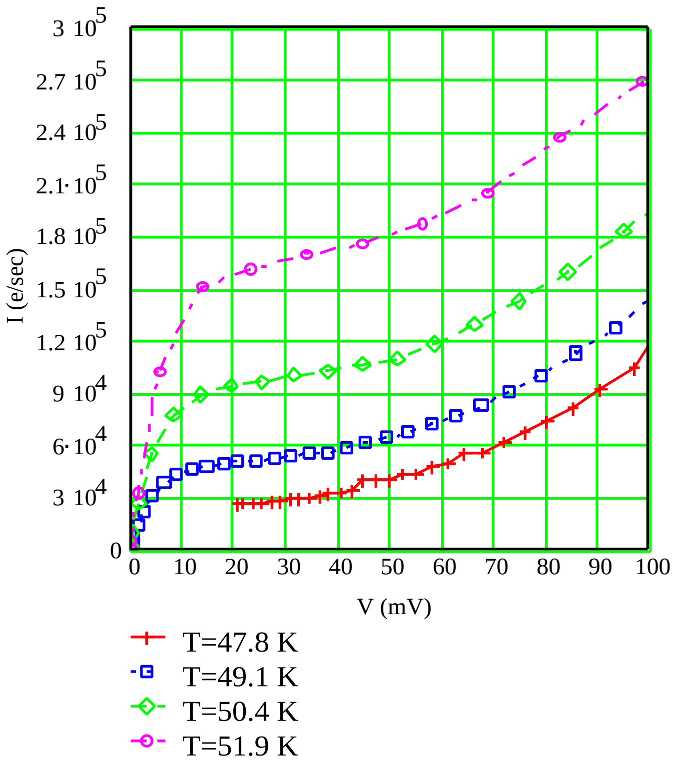
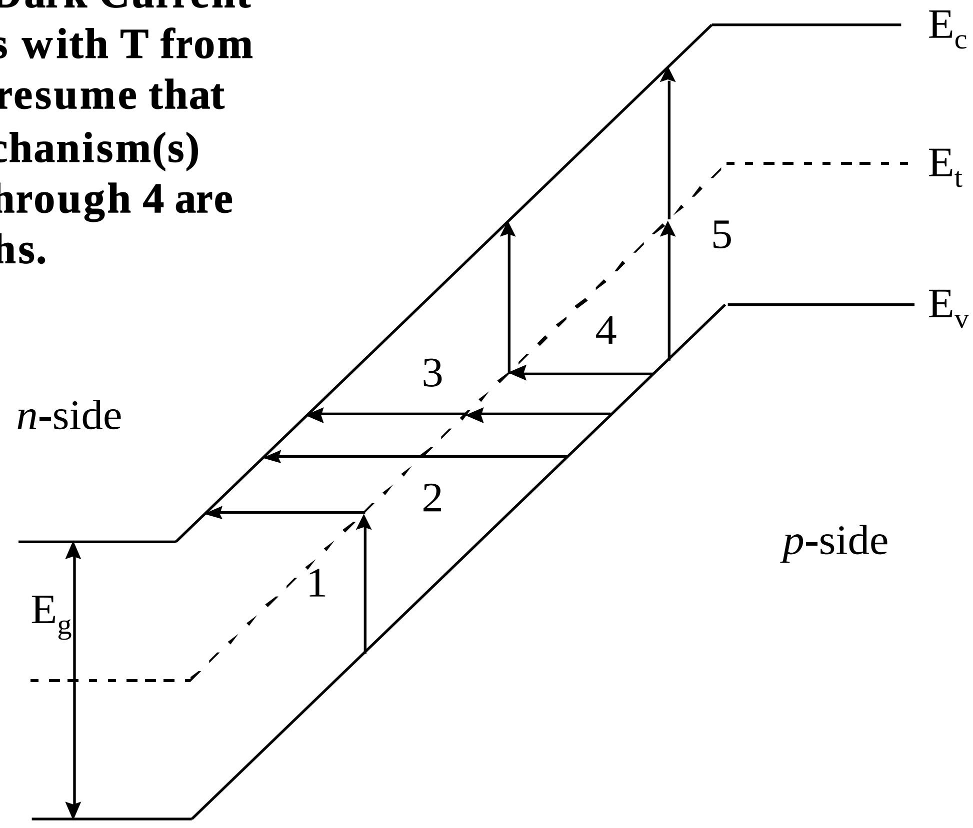
I-V Curves for Diode #15 as Function of T





Band to Band (2), Trap-to-Band (1,3,4) and G-R (5) Dark Current Mechanisms

From the flat Dark Current measurements with T from 20 - 40K, we presume that tunneling mechanism(s) dominate. 1 through 4 are tunneling paths.



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Model: Trap-to-Band Tunneling

$$-I_{TB} = AN_tW\frac{\pi^2 q m^* E M^2}{h^3(E_g - E_t)}\exp\left(-\frac{\sqrt{m^*/2}\,E_g^{3/2}F(a)}{2qE\hbar}\right)$$

q - electron charge

A - junction area

N_t - trap density

W - depletion width

m* - effective mass of holes

E_g - band gap energy

E_t - trap energy level (adjusted to fit data; = 0.037 eV)

M - a matrix element associated with the trap potential

F(a) - defines the trap level distribution

E - electric field at the junction and is *proportional to $N_D^{0.5}$*

- **Trap-to-band tunneling current increases rapidly with N_D**
- **Model shows fit to data for 100 mV back bias temperature dependence results for #15, as well as expected improvement for lower N_D**

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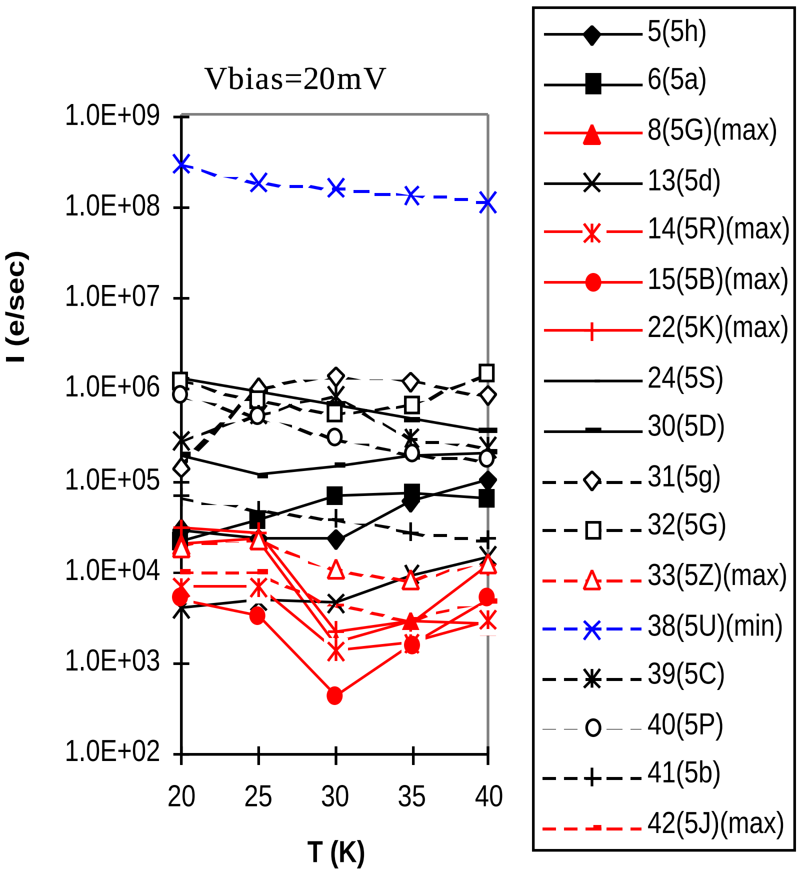
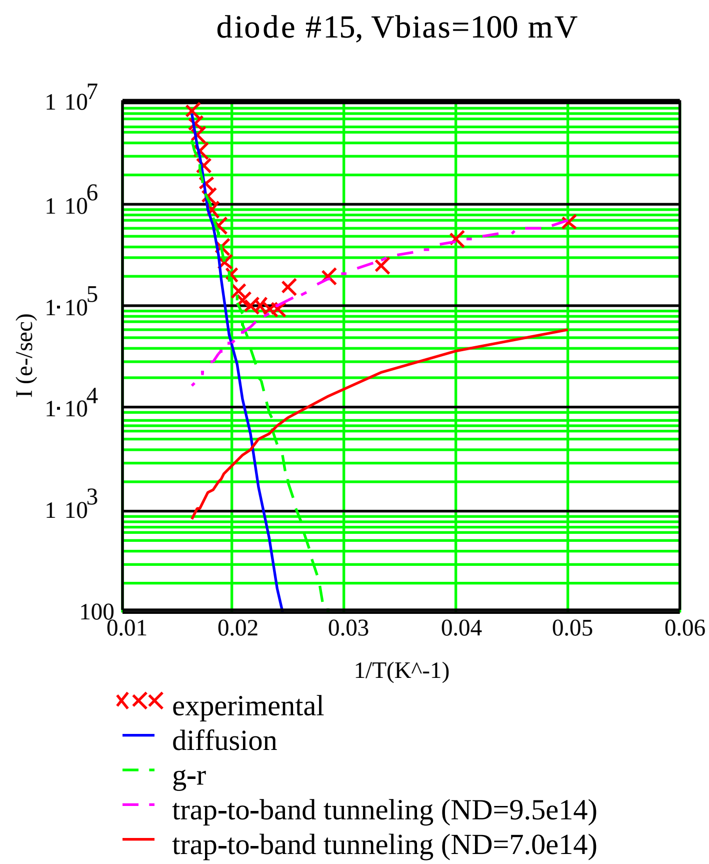
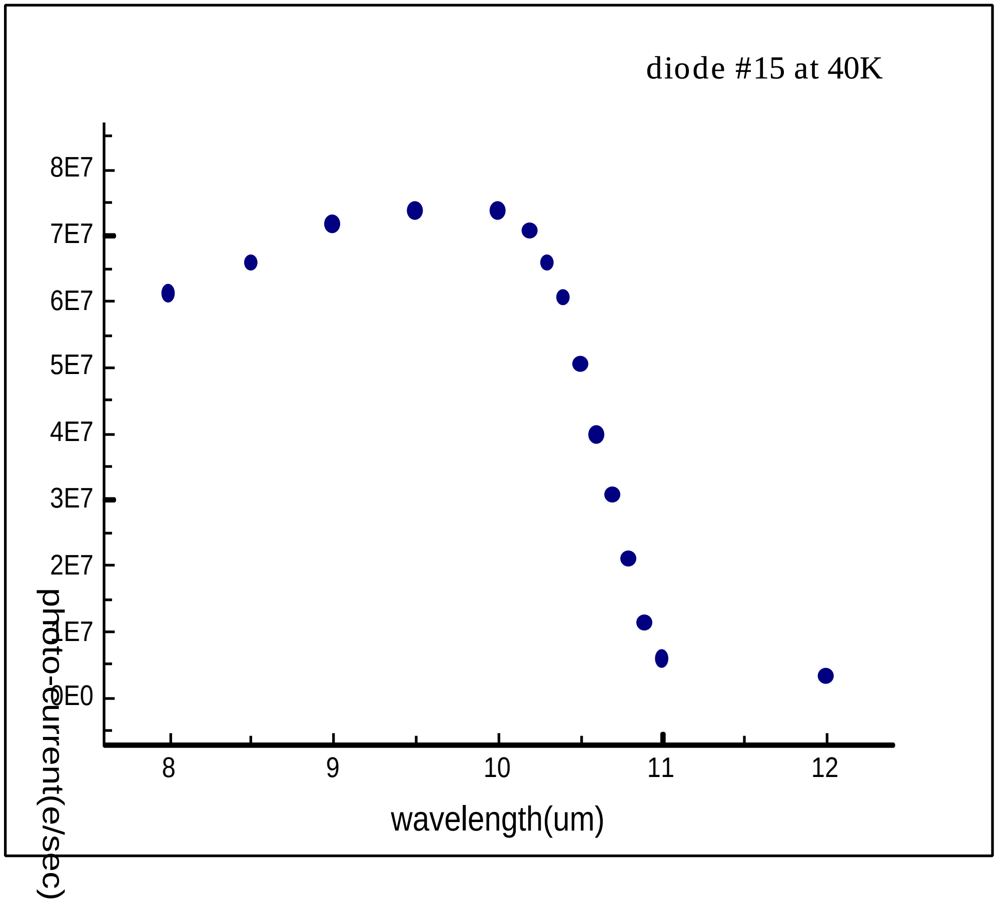
Test Results for Delivery 4: Dark Current *vs.* Temperature





Test Results for Delivery 4: Responsivity of Diode #15



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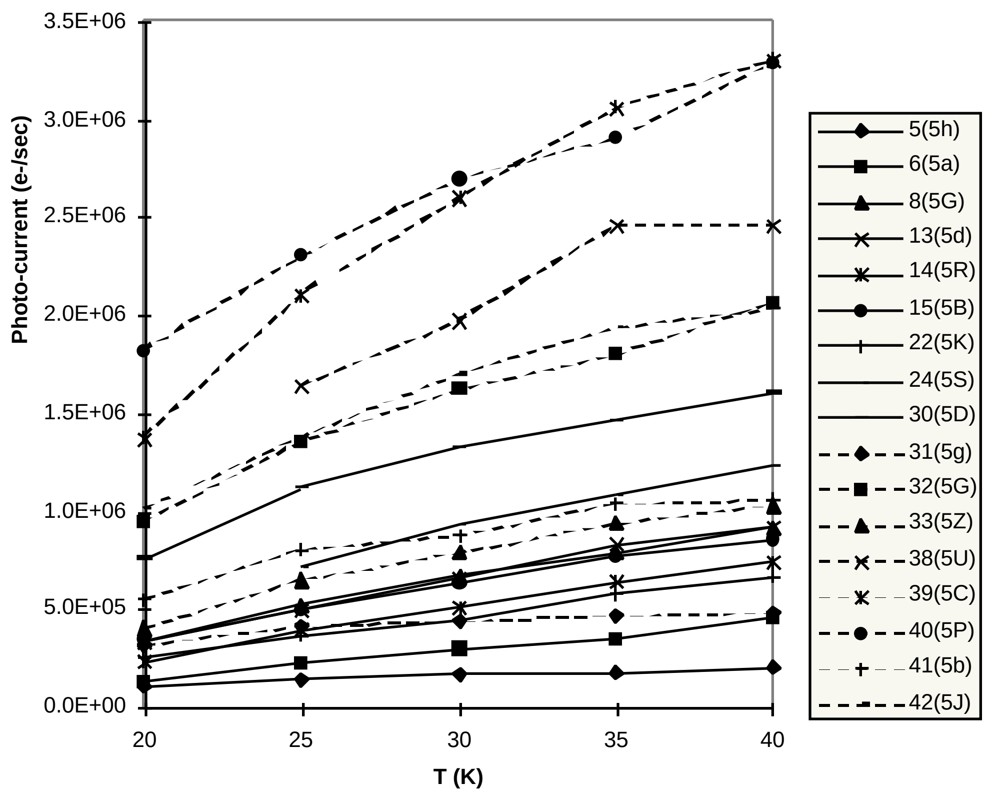
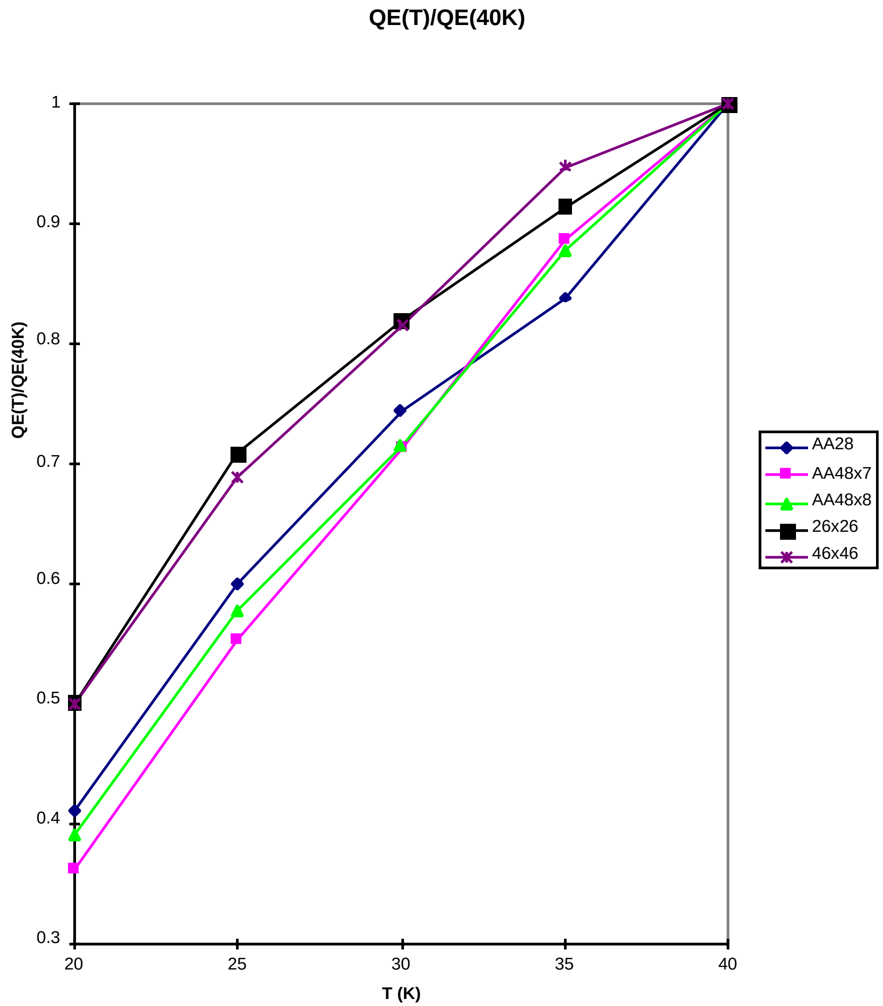
Test Results for Delivery #4: Photocurrent Temperature Dependence



Test Results for Delivery 4: Relative QE *vs*. Temperature



- **From 40 to 20 K, QE decreases by factor of 2 for most diodes**
- **QE of advanced architecture diodes has stronger temperature dependence**

Discussion

- **The diodes in delivery #4 show promise. Some diodes are close to satisfying space requirements [*e.g.* diode # 15 (5B), an advanced architecture diode, exhibits dark current < 440 e^-/s at 30K and 20 mV back bias, and QE(30K) ~70% QE(40K)].**

  ***We conclude from this and other observations that advanced architecture diodes are superior*:**

  » ***have lower dark current***

  » ***reasonable QE performance at lower temperatures***
- **Tunneling dominates the dark current, since dark current has strong bias dependence but weak temperature dependence.**

  Will try material with lower N_D
- **Deliveries 5 (and later) are focal plane arrays:**
  - **allow lower bias operation to minimize dark current**
  - **easier and more accurate capacitance measurement**
  - **back illumination, so that absolute QE measurements possible**